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COLLIDER PHYSICS

# Heavy-Ion Physics at CMS

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**Abstract**—We present a selection of recent results by the CMS collaboration on heavy-ion physics.

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The Compact Muon Solenoid (CMS) at the LHC is a general purpose detector very well suited for the study of heavy-ion collisions, its detailed description can be found in [1].

The average charged-hadron multiplicity densities at midrapidity in pPb collisions at nucleon-nucleon center-of-mass energies $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV with the CMS detector are compared to similar measurements in other experiments [2]. $\sqrt{s_{NN}}$-dependences for pp, pA, and AA collisions follow power laws. While the difference between the non-single-diffractive pp and pA results could be attributed to non-quark-gluon-plasma nuclear effects, the
similarity between the non-single-diffractive pA and total inelastic pp is to be understood.

The transverse energy $E_T$ density per participating nucleon-nucleon pair in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is also compared to other experiments and Monte-Carlo generators [3]. The rate of increase of the $E_T$ density with $\sqrt{s_{NN}}$ is stronger for AA than for pA collisions because of the increased stopping power of heavy nuclei compared to protons.

Long-range (pseudorapidity $2 < |\Delta\eta| < 4$), near-side (azimuthal angle $\Delta\phi \approx 0$) angular correlations ("ridge"-effect) were observed with the CMS detector in high-multiplicity pp at $\sqrt{s} = 7$ TeV [4] and pPb at $\sqrt{s_{NN}} = 5.02$ TeV collisions [5] (as well as in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [6]). The absolute "ridge" yield in pPb is significantly larger than in pp collisions of the same particle multiplicity.

Long-range single-particle azimuthal anisotropies in ultraperipheral pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV were studied with CMS detector [7]. The single particle elliptic flow coefficient $v_2$ increases with transverse momentum $p_T$ and is larger for $\gamma$p-enhanced events than for minimum-bias collisions of comparable multiplicity. These results extend the search for collectivity in small systems to $\gamma$p events.

The mixed higher-order anisotropic flow and nonlinear response coefficients of charged particles are measured as functions of $p_T$ and centrality in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV with CMS detector [8]. The viscous hydrodynamic calculation with Glauber initial conditions and shear viscosity does not provide a simultaneous description of the mixed higher-order flow harmonics and nonlinear response coefficients.

Azimuthal correlations of charged particles in XeXe collisions at $\sqrt{s_{NN}} = 5.44$ TeV were studied [9]. The magnitude of the $v_2$ coefficients for XeXe collisions is larger than those found in PbPb collisions for the most central collisions. This is attributed to a larger fluctuation component in the lighter colliding system.

A significant positive $v_2$ signal from long-range azimuthal correlations is observed for all particle species in high-multiplicity pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [10]. The results suggest that charm quarks have a smaller $v_2$ than the lighter quarks. For $p_T = 2$–$5$ GeV/$c$, $v_2$ for nonprompt

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$D^0$ mesons are smaller than for prompt ones. $v_2$ characterizing the azimuthal distribution of $\Upsilon(1S)$ and $\Upsilon(2S)$ arising from PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are studied [11]. In contrast to the $J/\psi$, no azimuthal anisotropy is observed for the $\Upsilon$ mesons.

The cross sections for $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ production in PbPb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV have been measured [12]. The nuclear modification factors, $R_{AA}$, derived from the PbPb-to-pp ratio of yields for each state, are studied as functions of meson rapidity and $p_T$, as well as PbPb collision centrality. The yields of all three states are found to be significantly suppressed, and compatible with a sequential ordering of the suppression. No sign of $\Upsilon(3S)$ was found in PbPb collisions.

Production cross sections of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ states produced in pPb collisions are reported at $\sqrt{s_{NN}} = 5.02$ TeV [13]. All states are found to be suppressed in pPb compared to pp collisions with the same collision energy. The suppression of all $\Upsilon$ states in PbPb collisions is the largest when compared with pPb collisions. The final-state comover interaction model, which predicts sequential suppression of bottomonia in pPb, is found to be in better agreement with the data than initial-state models. The nuclear modification observed in pPb collisions is less pronounced than the strong modification observed in PbPb collisions, suggesting the presence of additional quark-gluon plasma effects in the latter.

The first evidence for $\chi_{c1}(3872)$ in heavy-ion collisions is reported with the CMS detector in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [14]. The statistical significance of the $\chi_{c1}(3872)$ signal is in excess of 3 standard deviations. The production and survival of the prompt $\chi_{c1}(3872)$ in the quark-gluon plasma is expected to depend upon its internal structure. It is a unique experimental input to the theory, towards elucidating the production mechanism and the nature of $\chi_{c1}(3872)$.

The $B_s^0$ and $B^+$ production cross sections are measured in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the CMS detector [15]. The $B_s^0$ meson is observed with a statistical significance in excess of 5 standard deviations for the first time in nucleus-nucleus collisions. No significant $p_T$-dependence of the $B^0/B^+$ ratio was found. The ratio of production yields for $B_s^0$ and $B^+$ in PbPb collisions is found to be statistically compatible with the corresponding fragmentation fraction ratio.

First-ever evidence for the production of top quarks in nucleus-nucleus collisions, using PbPb at $\sqrt{s_{NN}} = 5.02$ TeV is presented by the CMS experiment [16]. The measured cross sections are compatible with expectations from scaled pp collisions and QCD predictions.

Jet production in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV was studied with the CMS detector [17]. Central collisions show a strong imbalance of leading and subleading jet $p_T$ ("jet-quenching" effect). The dijets in central collisions are found to be more unbalanced [18]. Measurements of jet nuclear modification factors based on pp and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are presented by the CMS experiment [19]. For the most central PbPb collisions, a strong suppression is observed for jets with high $p_T$ reconstructed with all distance parameters.

## CONCLUSIONS

To summarize, we can say that the investigation of heavy-ion collisions with the CMS detector during the first two stages of its operation (Run 1 and 2) led to very interesting results of hadron matter under extreme conditions. It is expected that new information of no less interest will be obtained after the beginning of the new runs with the upgraded CMS detector and new energies and luminosities of the LHC. All of the CMS heavy-ion papers can be found at the CMS website [20], as well as preliminary results [21].

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## CONFLICT OF INTEREST

The author declares that he has no conflicts of interest.

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